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Lasers for Wireless Power Transmission

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Currently used for communications, lasers are also highly promising for wireless power transmission and off-board space propulsion, but safety concerns must be dealt with first.

power beam safety

Introduction

Low-power lasers are widely used today for telecommunications, as well as for low-cost laser pointers and laser light shows. Higher-power lasers are employed in surgery, and to cut, weld, and heat metal. More recently, a ground-based pulsed carbon dioxide laser has boosted research "lightcraft" to altitudes higher than Goddard's first rocket. Lasers are now being considered for wireless power transmission, propulsion, and space exploration.

A potential application of particular interest is the use of lasers to beam power from solar collectors in space to other locations, both in space and on the Earth's surface. The concept of space solar power systems for terrestrial power delivery was first proposed by Glaser in 1968 and studied extensively by NASA, the Department of Energy, and others in the 1970s and 1980s. It was recently revisited by NASA in a "Fresh Look" study (see *Aerospace America*, May 1997, pp 30-36), and was subsequently elaborated further by the agency in a follow-on Concept Definition Study during 1998.

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These space solar power concepts require a means for transmitting the electric power that is converted from solar energy by the space-based power conversion system (e.g., photovoltaic arrays) to the Earth's surface for subsequent terrestrial distribution as electric power. All the concepts studied to date, from Glaser's initial proposal to the 1998 studies just completed, have employed microwaves to meet this wireless power transmission requirement. Laser beams have both advantages and disadvantages *vis-a-vis* microwave beams for power transmission.

Pros and cons: lasers *vs* microwaves

Size reduction. By far the most important benefit of laser beaming over microwaves is the reduction in size of the transmitting and receiving antennas. The beam diameter needed to carry a given amount of power varies approximately with the wavelength of the beam. Because the wavelengths of lasers are about 5 orders of magnitude shorter than microwaves, the power transmitter and receiver can be much smaller; that is, meters rather than kilometers in diameter for power levels in the hundreds of megawatts. The diffraction of a power beam also varies roughly with wavelength, so the spreading of a laser beam will be much less than that of a microwave beam. For distances that may range up to 35,000 km (for a geostationary-orbit power satellite), this reduces the receiving antenna's land-area requirements still further, with obvious cost-reduction consequences.

The size reduction of the space-based transmitting antenna also has significant cost-reduction impact. In volume-limited space transport, for example, an entire laser system could be orbited in a single launch.

The ability to field smaller systems may also allow a lower total power level laser system to be economically competitive with a much higher power microwave system in terms of both installed capital cost (\$/kW) and operating cost (cents/kWh).

Interference. A major issue in space solar power systems employing microwave power transmission is their potential interference with satellite communication systems, which use frequencies in the same multi-gigahertz range that is best suited to microwave power transmission. The filtering and/or frequency restrictions necessary to avoid such interference could be a major barrier to the economics of space-based power systems for terrestrial consumption, and obtaining their approval by the Federal Communications Commission and the International Telecommunications Union may be extremely difficult due to the potential interference with the ubiquitous global satellite communication services.

Lasers, however, avoid these interference issues, both because of the great disparity in fundamental frequencies between lasers and satellite communications bands (a difference of roughly five orders of magnitude) and the fact that the narrow laser beams are less likely to have significant sidelobes that could introduce interference. Also, should national sovereignty become an issue, the much smaller laser-beam sidelobes are less likely to spill energy over adjacent international borders.

Atmospheric and weather effects. Both microwave and laser beams are attenuated by the Earth's atmosphere and its weather-dependent particulate content. Attenuation due to scattering is highest when the wavelength is comparable to the size of the particles in the atmosphere. Because of the much shorter wavelength of laser beams, they are much more severely attenuated than microwave beams, to the extent that power beam interruptions to the terrestrial utility station will occur.

The longer-wavelength microwaves pass through rain and clouds with only small attenuation and scattering. Glaser's original concept and the early NASA/DOE studies were based on microwave power transmission at 2.45 GHz, a frequency whose wavelength is long enough to be nearly unaffected by weather. However, the abovementioned interference considerations and

size-related system economics may dictate the use of higher microwave frequencies, which could introduce greater weather effects.

But these effects on microwave-based systems would never be as severe as with laser transmission. As a result of their greater sensitivity to weather-induced attenuation, baseload electric utility systems employing laser power transmission will require many spatially diverse receiving sites to deal with weather outages. One approach would be to use ground-based energy storage; another is to transfer power from clear sites via an interconnected ground network. The incremental costs of either of these "fixes," along with the need for multiple sites, could compromise the economics of systems that use laser power transmission.

Safety. Power beam safety is mandatory for both laser and microwave beams. Because the power flux density of a laser beam is much higher than that of a microwave beam for the same total power delivered, the consequences of any intrusion into the beam by people, animals, or artifacts can be much more serious for the laser than for the microwave beam. The physical laws that allow the laser beam diameter to be so small also make the microwave beam power per unit area lower, and hence potentially less damaging.

One advantage of the laser beam, however, is that if the wavelength of operation is suitably selected it is clearly visible due to diffraction by the atmosphere's normal aerosol content. The microwave beam is invisible and can only be felt by its thermal effects.

Geopolitics. High-power space-based lasers will face political as well as safety challenges. For example, any space-based laser must comply with the treaty constraints of the 1972 US-Soviet anti-ballistic missile (ABM) treaty that prohibit space-based defenses having the ability to intercept long-range (strategic) ballistic missiles. Since the economics of wireless power transmission are highly dependent on the transported power level, any potential

limitations must be known before investors would contribute to commercial laser beamed power developments.

Technical maturity. The relative immaturity of laser power transmission technologies relative to those associated with microwave power beaming constitutes the major current barrier facing the implementation of lasers for this application. However, major strides have been made in recent years in both military and commercial development programs. The overall efficiency of a laser power transmission system (from incident sunlight to the terrestrial power grid) is now estimated to be more than half that obtainable with a microwave system, and the technology continues to improve.

Alternatives to “conventional” satellite power

One alternative to Glaser's overall system architecture, which has been the conceptual baseline for virtually all subsequent studies, was the senior author's suggestion that space-based laser beams transmit power to the coal-pile yards of existing steam power plants. Economics drives conventional space solar power concepts to very high power levels (typically one to ten GW), but it has been suggested that lasers could perhaps be built economically at smaller power levels (e.g., 125 MW, like a modest steam power plant). Furthermore, the laser power-beam receiver could be small enough to share the coal yard of a plant. With suitable conditioning, the laser electric power output from orbit could tie into the electric utility's existing metering, switching, and distribution infrastructure.

An orderly transition from an all-coal plant to a combined coal and laser plant should aid the utility economics and minimize the disruption of offsetting coal-fired electric power generation. Also, the plethora of coal-fired plants in the U.S. would permit the transfer of power over the grid to work around laser outages due to weather-front movement.

Eventually, the steam plant's boilers may be able to be redesigned to be heated either directly by the laser beam from space or by the customary fossil-fuel furnace. This approach would resolve the ground energy storage issue for laser powered systems. The loss of the laser beam could be used as the trigger to ramp up the fossil-fuel furnace, with the steam vessel providing the thermal capacity to smooth over the transition. Although thermal-energy laser conversion to electricity may not be as efficient as tailored-wavelength photovoltaic conversion, the economics may favor thermal conversion when the cost of energy storage is factored in.

Safety considerations for laser power transmission

Space-to-space laser power beaming should use wavelengths that are strongly absorbed by the Earth's atmosphere, so as to prevent illumination of biota on the ground. For space-to-Earth beaming, wavelengths that are *not* strongly absorbed are desirable, but this makes their beams potentially dangerous, requiring careful attention to safety features.

Laser beams that are economically useful for power transmission and transportation will be of high intensity. They therefore pose a potential hazard to unprotected personnel, other biota, and equipment. Consequently, fail-safe means must be provided that automatically shut off the beam, spread it out, or divert it from potential victims.

Where possible, physical barriers, exclusion zones, warning signs, audible warnings, high-frequency noise irritants, odor warnings, warning lights, hazard markings, etc should be used to the extent possible to keep personnel and other biota from the intense power beam. Conditioned responses may have to be promulgated for the affected populace.

Barriers and warnings are not in themselves sufficient to assure beam safety. Surveillance to detect potential interactions of the beam with victims is also required, with due regard for the finite round-trip time delay in turning off the beam. The hazard is the remaining energy that is already in transit from space to ground.

Properly functioning sensors are needed to detect imminent collisions of beams with objects to be protected. This includes not only the primary beam, but also any scattered portion of the beam that is of sufficient intensity to pose a vision or other hazard. Accurate beam impact predictions require high signal-to-noise-ratio acquisition and tracking of potential victims, including good prediction of their trajectories.

The quality, quantity and locations of surveillance equipment and techniques must be scaled to the objects to be detected. These will obviously include not only personnel, their various forms of air and space transportation vehicles, and space platforms or stations, but also perhaps birds and bats and possibly even insects such as butterflies, although it would almost certainly be uneconomical to build protection subsystems for such small airborne biota. Detailed environmental studies will need to be made, considering the various trades to society.

Furthermore, to assure that such sensors are operating satisfactorily, they must be tested frequently. Thus, interlocked beam testers, sensors, and shut-off switches are required for laser beam safety.

One approach to a beam tester design could be miniature beam-powered helicopters, equipped with Global Positioning System (GPS) electronics, that live right in the beam and drift horizontally back and forth at the beam edges like insects hovering around an outdoor night-light. They would transmit continuous information on their location and the beam intensity to the beam transmitter control, so that the beam can be turned off if it wanders or intensifies

Air traffic control systems and eventual space traffic control systems must be tied into laser power beam utilities for safety coordination of movements of personnel and equipment. Laser beam sites should be located away from avian migratory routes and scheduled airline routes. One should try for restricted airspace locations, but even then, in an air emergency situation, an errant overflight of a troubled 747, for example, should be given priority over an electric power beam.

(Note that the danger to aircraft flying through the beam is primarily the deleterious effects of the laser on the eyes of people in the aircraft, and possibly effects on critical instrumentation, but not "zapping" of the aircraft itself. The time spent in the beam is so short that even if the full power of a 10-m diameter, 500 MW laser is absorbed by a small commuter aircraft flying through it, its skin temperature would rise no more than a degree or two.)

One of the implications of the foregoing approach to laser beam safety is that the systems utilizing the beams must be prepared for unannounced power delivery interruptions. This means, for example, that power-beam electric utilities must be prepared for the tremendous transients that sudden interruption can engender. Less of a problem, but also of concern, are the transients that occur in reestablishing the power delivery.

The implications of interrupted power delivery for transport vehicles powered by laser beams include the ability to change trajectories and coasting time, the need to implement emergency descent procedures, the requirement to carry on-board energy storage systems, etc.

Both periodic and random beam testing are recommended to verify the status of the safety system. In fact, if the general public is to accept the presence of high-power laser beams in their midst, then they should be encouraged to initiate a beam test event by having many locations from which to do so, and they should be apprised of the result immediately. Such participatory safety systems do not exist in any other public utility context, and would

require substantial development and evaluation as well as allowance for their incremental cost.

Furthermore, it is strongly recommended that power beams to Earth be visible (green, for example) so that the general populace can be aware of their steady location when operating. This will help to allay the fears of unseen "beam wandering" off the designated receiving sites. Even if the high-power beam is at wavelengths longer than visible, it should be coaxially surrounded with a visible-color beam to aid in public recognition of the potential hazard.

Active auditing of launched and received total beam power is recommended, implying development of the required power-measuring instrumentation to meet accuracy and reliability specifications.

To assure that the power beams are indeed delivered to their designated sites continuously, reliably, and without any chance of "wandering," the power transmission devices must be retrodirective phased arrays; that is they will not operate without a pilot safety signal that is transmitted from the ground receiver to the space-based transmitter. Although a single continuous-aperture beamer could be used, the many elements of a phased array assure rapid, incoherent beam spreading whenever the phase reference provided by the pilot safety signal is not present, thereby dispersing the generated power harmlessly. Furthermore, the inherent electronic beam-steering capability of a phased array allows rapid shutdown and re-establishment of a laser beam to its alternate weather site without mechanically repositioning the satellite. The pilot safety signal can be coded and of such a magnitude that a terrorist could not easily duplicate it for destructive purposes.

For additional safety, the system can be designed to require a fairly high-power uplink beam to be radiated from the receiver, such that it "primes the pump" at the transmitter for producing downlink power. If the uplink is absent or degraded, no output is

forthcoming. The uplink must be of sufficient magnitude to overcome a prescribed threshold for spacecraft power production.

All safety systems should be designed to fail safe; i.e., no response, no beam.

In some applications it may be possible to utilize a high-altitude stratospheric platform as a power relay platform, wherein the long hop to or from space is made with laser beam, and the short hop -- platform to or from the ground -- is made with a much wider and less-intense microwave beam. In addition to its somewhat less stringent safety considerations, the microwave beam can in this case suffer less atmospheric loss and will provide more consistent all-weather beamed power operation.

The availability of laser power delivered from space to Earth will be affected by the cascade of safety interlocks, meaning that there will often be false alarms, but that may well be a reasonable price to pay for electric power alternatives to greenhouse-gas emissions, for example.

Technology

Solar-pumped lasers. A significant potential gain in efficiency of a space-based laser wireless power system could be effected if the laser could be pumped directly by solar energy instead of by electricity derived from photovoltaic arrays. It was recently reported (see *IEEE Spectrum*, May 1998, pp 23-32) that researchers at the Energy Research Center of the Weizmann Institute have built and tested solar pumped lasers with efficiencies up to 30% and power in the kilowatt range. These lasers are currently multi-spectral. They estimate that the conversion efficiency in space, above the Earth's atmosphere, would currently be about 20%, which exceeds the composite efficiency of the "conventional" solar-to-electric-to laser concept.

Laser component technology. The Air Force is developing chemical lasers in the megawatt power range for airborne and space-based laser weapons. Such lasers would not be optimum for electric utility use due to their need for frequent refueling. However, the technologies being developed by these programs for cooling the high-power mirrors, building and testing the adaptive optics needed for efficient transmission through the atmosphere, and devising fast, accurate tracking and acquisition techniques are directly applicable to laser-beam electric utility and transportation applications.

Researchers at the University of Vienna have recently completed the design and testing of a 16-element retrodirective optical phased array for space intersatellite-link communication. This technology is directly applicable to the laser power beam safety requirement (see above), and has only to be scaled in quantity of elements, their aperture packing, and their power handling capabilities.

Orbital laser beam geometry

As with any space solar power system employing wireless power transmission, the laser power beamer has a fundamental geometrical constraint. As the spacecraft orbits the Earth its coherent output power beam must be directed toward the Earth-based receiver, while its solar power collector must be pointed toward the Sun. The changing angle between the Sunward direction and the power-beam direction can be accommodated by a reflector system having a rotary joint. The reflectors could be on the output power side or the input power side of the spacecraft. Because the sunlight is non-coherent energy, it is easier to put the mirror on the input side. Aiming tolerances can be larger, and pointing variances are more forgiving.

Another system geometry consideration is the ratio of the solar collector aperture to the coherent beam radiator aperture.

Sunlight is diffuse: its power flux density in the geostationary orbit (GEO) is about 1.37 kW/m^2 . To estimate the size of the collector, assume that for a system that is to deliver 125 MW to the electric grid the ground-based photovoltaic conversion efficiency is 60%, the photovoltaic-to-ac-grid conversion efficiency is 95%, the beam coupling efficiency is 90%, the atmosphere transmission is 90%, the laser transmitter's aperture efficiency is 85%, and the sunlight to optical conversion efficiency (assuming an advanced developed solar-pumped laser) is 55%, then a sunlight collector aperture of about $375,000 \text{ m}^2$ (a diameter of 680 m) is required.

The physics of diffraction, however, dictate that the diameter of the laser beam at the receiver will be inversely proportional to the diameter of the laser transmitter. That means that if, for example, a 1-m diameter, 0.5-micron laser beam were transmitted from GEO, the half-power focused spot diameter on the ground would be 18.75 m in diameter, while a 0.5-m beamer would produce a 37.5-m spot and a 2-m beamer would yield a 9.38-m spot.

But collecting sunlight from a 680-m-diameter collector, at the assumed stackup of efficiencies, means that with the on-orbit conversion efficiency of 55%, to deliver 125 MW to the grid requires that 231 MW of waste thermal heat must be dumped to space. Hence a rather large thermal radiator must compete for field-of-view with the laser output beamer and the solar input collector. The actual size of the thermal radiator is determined by the heat rejection temperature, which is related to the lifetime of the sunlight-to-laser conversion equipment. A pumped-fluid thermal control system would almost certainly be required, with its additional mass, complexity, and reliability issues.

The thermal energy dissipation problem could be somewhat relieved by intentionally spreading the beam from the laser transmitting array to yield a more uniform power flux density on the ground; that is, flattening the normal Gaussian flux density distribution of the beam into a more rectangular shape. Because this would require a larger-diameter beamer than the typical

Gaussian shaped beam, the thermal radiation flux density at the source can be reduced.

Even greater spreading, as well as a larger-diameter transmitter, may be required so as not to exceed some prescribed peak power flux density limit in the beam. This is exactly the converse of the microwave power transmitter design, which strives to focus the beam as tightly as possible to keep the diameter of both transmitter and receiver as small as possible.

Even though a small single-aperture laser transmitter could be used, we have noted that safety considerations dictate an aperture consisting of many small phased array elements. For an array with N elements, the power flux density drops as $1/N$ when the phased array goes non-coherent. To reduce the average beam intensity to no more than that of sunlight at the Earth's surface at noon on a clear day ($\sim 1 \text{ kW/m}^2$), the array must consist of at least 450 elements.

Many small incoherent laser power transmitters (not phased-array elements) could be utilized, simply adding their power incoherently at the ground receiving site, but the resulting combined beam spot intensity would lack the inherent beam safety feature of the retrodirective phased-array pilot signal. For this type of transmitter one could reduce the incoherent beam spot intensity only by turning off the lasers or by spatially mis-pointing the many beams. Misdirecting a common beam-turning mirror would dim the combined laser outputs, but would probably take too much time. That is, too much power in the beam could still arrive after transmitting the "reduce beam" command before the beam density would drop to a safe sunlight-equivalent level.

Future space laser applications

Interstellar exploration. Missions using currently known physics involve photon-driven light sails powered by very large, high-

power beaming systems. Forward suggests a design in the *Journal of Spacecraft & Rockets*, Mar.-Apr. 1984, pp. 187-195, for an Alpha Centauri flyby using a 1000-km-diameter lens fed with a 65-GW space-based array, yielding a power beam able to send a 1000-kg spacecraft having equal parts of sail, support structure, and payload on a 40-year mission at 11% of light speed.

The senior author is investigating an alternate configuration for the beamer that uses a phased-array approach. The array would consist of a circular ensemble of tightly packed, low-mass inflatable optics elements, each equipped with injection-phase-locked solar-pumped lasers, operated in a quasi-retrodirective method by use of pilot signals from a fleet of periodically refreshed microspacecraft far in front of the beamer. Due to aberration, the phased array is not truly retrodirective in that the beam must be pointed where we wish the beam-riding sail to be in the future, not where the reflection came from in the past.

By diplexing the optics of the beamer elements, it should be possible to have the beamer also operate as an imaging telescope to survey the target interstellar system, thus increasing the science yield of the mission. Operating the beamer as a lidar would greatly increase active radar science at short wavelengths.

Note that the power beamer's mass for these interstellar missions is of such magnitude, even with lightweight optics (typical estimate: 1.6 billion tonnes), that it would probably have to be manufactured in space from an Earth-crossing metallic asteroid such as 6178 1986DA. This 1.5-mi-diameter asteroid is estimated to contain 10 billion tons of iron, one billion tons of nickel, 100,000 tons of platinum, and 10,000 tons of gold.

Planetary defense. Another use of such a phased-array laser beamer may be to focus intense power on the surface of potential Earth-impacting asteroids or comets, creating jets of heated material having enough mass and velocity to change the object's orbit sufficiently to miss the Earth. Care would of course have to

be taken to ensure that the object's composition would not favor fragmentation rather than the desired whole-body motion.

Commercial uses. The power from space-based laser power "depots" could also be used to deliver power to next-generation high-power communication satellites and space stations or platforms, to support bases on the Moon, Mars, and perhaps satellites of the gas-giant planets, and to support assaying and mining missions to asteroids. Laser power beamers, used with various forms of propulsive devices, could transport materials from the Moon or asteroids to space-based manufacturing facilities, and could meet space tourism transportation needs by rapidly moving guests and their support materials among the moons and planets of the Solar System.

Conclusions

Consideration of laser wireless power transmission. Space solar power and propulsion concepts which require wireless power transmission should be expanded to include serious consideration of laser beam systems, supplementing the current evaluation of microwave power transmission. This will require allaying public perception fears via educational demonstrations of real safety systems, including but not limited to those listed in the table.

In this connection, it is important for everyone to recognize that all high-power energy transmission systems (e.g., high-voltage ac transmission lines, gas pipelines, oil tankers, coal trains, rivers, belts, pulleys and shafts, etc) are inherently dangerous, but under controlled circumstances and with the proper safety systems, they are very useful to society. Laser and microwave beams can be safe also, if properly engineered and operated and if the appropriate steps are taken to educate and inform the public.

Technology and demonstrations. The technologies for all the elements of a space-based laser power transmission system are

available, including the pilot-beam safety system, with the exception of the beam tester interlock functions. What is now needed is a commercial "carrot" to set things in motion; i.e., ground-based demonstrations and test facilities. These should be open to public inspection, and should be made portable for education and public outreach at various public fora.

[TABLE] LASER BEAM SYSTEM SAFETY ELEMENTS

1. Exclusion zones; restricted air space
2. Physical barriers; e.g., chain-link fences
3. Warning signs denoting eye safety hazard
4. Audible warnings; e.g., klaxons, bells, chimes, instructions
5. High-frequency noise irritants to frighten birds away
6. Odor warnings, with similar goals
7. Warning lights; e.g., rotating beacons
8. Hazard markings; e.g., zebra striping
9. Conditioned-response education, to inculcate "duck and cover"
10. Active surveillance; e.g., radar, sonar, observers
11. Interlocked beam testers, both scheduled and public-initiated
12. Continuous beam sensing by random helicopters in the beam
13. Kill switches in affected areas
14. Fail-safe designs: no response, no beam
15. Traffic coordination via airspace and space traffic control
16. Avoid obvious existing traffic routes such as avian migratory paths and air traffic corridors.
17. Visible power beam; i.e., 0.4-0.7 micron wavelength
18. Active auditing of power launched and received
19. Pilot beam and retrodirective phased-array
20. High threshold pilot signal level to "prime the pump"
21. High absorption wavelength for space-to-space beams
22. Stratosphere power-relay platforms: laser to and/or from space, microwave to and/or from the ground



TABLE MOUNTAIN UPLINK BEAM (JPL OPTICAL COMMUNICATIONS GROUP)

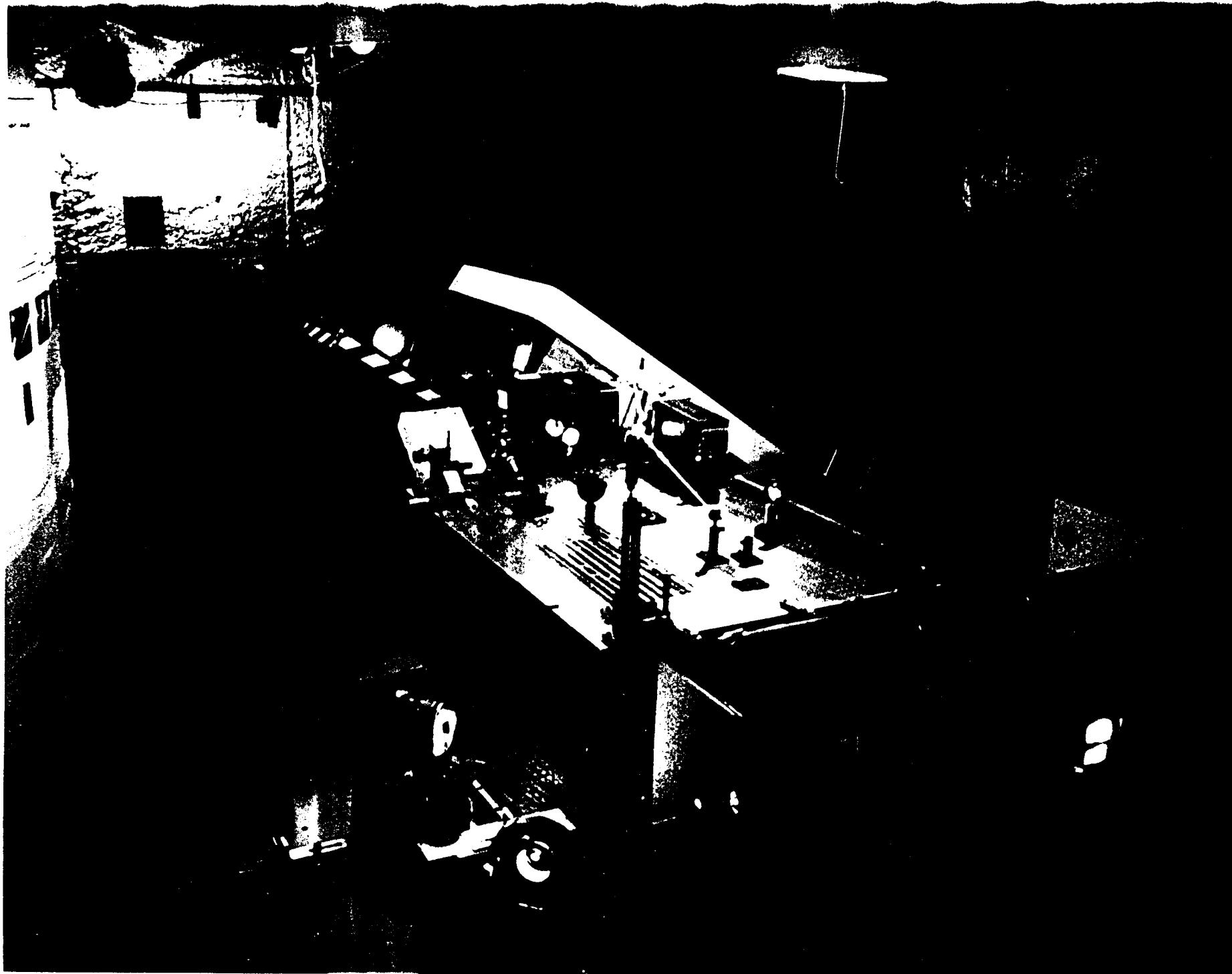


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